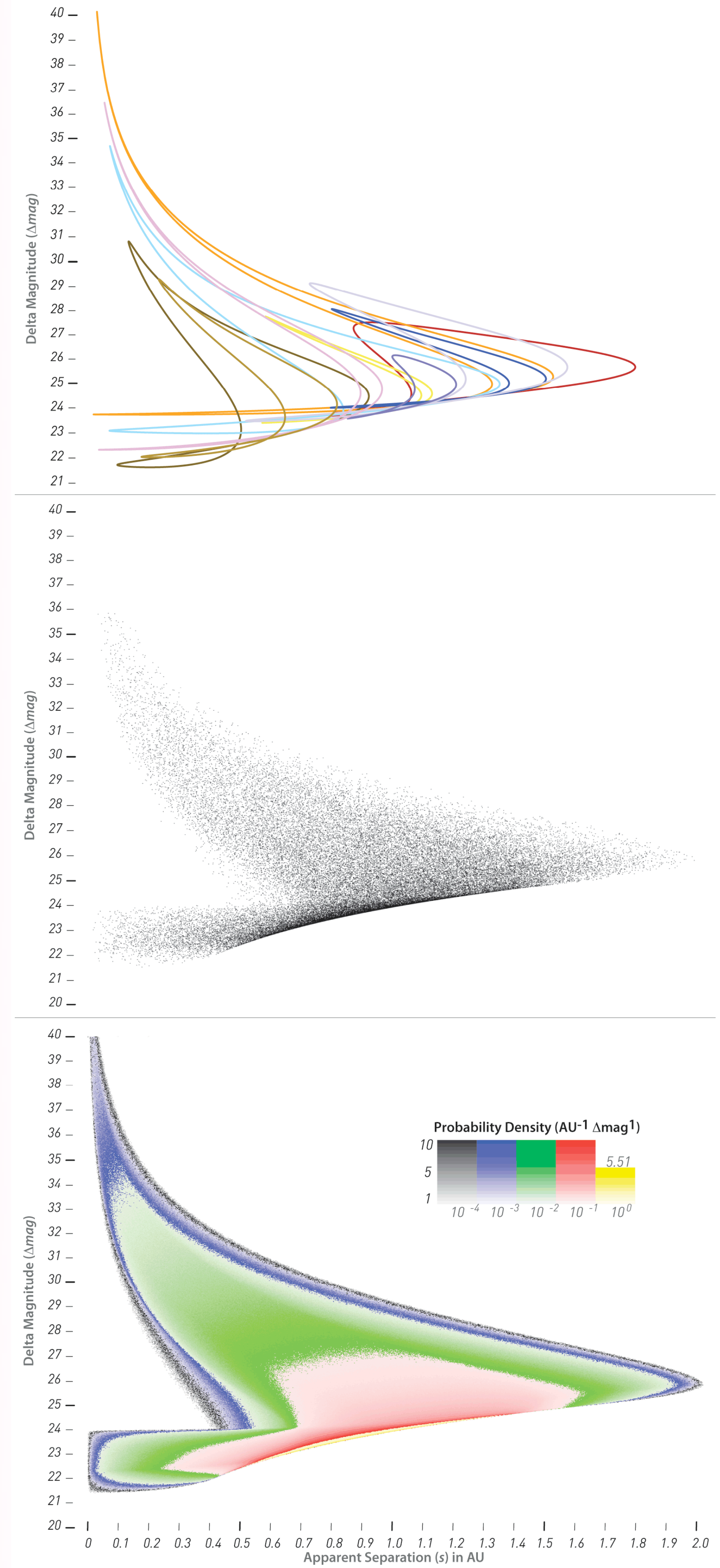
Mission Studies for TPF-C

Robert Brown, Stuart Shaklan & Sarah Hunyadi

September 28, 2006



Overview

- Goal: to determine the *natural metrics* for *TPF-C*
  - from the phenomenology of habitable-zone, Earth-like planets
  - from the known characteristics of the given nearby stars
- Methodology: simulate the use of *TPF-C* to achieve science requirements
  - *mission modeling* of *science operations*
- Technical drivers
  - small number of stars with habitable zones resolved by 4-8m aperture
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  - planetary variability (separation, brightness)
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  - discovery (detection)
  - confirmation (disambiguation of confusion, planetary recoverability)
  - characterization (spectrum, orbit)
- Responsive aspects of design (and candidates for natural metrics)
  - deep sensitivity @ small angles @ high throughput (completeness/time)
  - agility & flexibility (low overheads, wide pointing latitude)
  - high astrometric accuracy (confusion, orbit, recovery)

Scope of workshop

***TPF-C* instrument**

- IWA, inner working angle
- OWA, outer working angle
- $\Delta\mathrm{mag}_0$, systematic limit
- λ & $\Delta\lambda$, bandpass
- A_{eff}, effective area
- ζ, star suppression
- SNR calculation
  - Ψ, sharpness
  - $\varkappa$, sampling
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- $\Delta\theta$ calculation (astrometry)

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TPF-C **instrument**

Science operations

- Science priorities
- Rules, constraints & restrictions
  - solar avoidance
  - observational overheads
- Observational protocols
- Data analysis scenario
- Scheduling algorithm

Sky

- Stars
- Planets of interest
- Planet occurrence rate
- Background confusion
- Exozodiacal light

Mission studies provide the scientific context, calculations, issues, and natural metrics for estimating the scientific productivity of an instrument.

Mission modeling

This set of information constitutes a complete working description of the *TPF-C* mission, *including outcomes modulo* η_{Earth}.

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The Project will draw from instrument teams the specifications needed for mission modeling to evaluate natural metrics to help optimize *TPF-C* in terms of whole mission science.

Provenance of input specifications

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Instrument teams

→

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Common agreement

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Nature, given

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DRM completeness calculations

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Completeness

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The completeness is the detectable fraction of all possible planets of interest.

Future modeling must include non-constant throughput and background in the annular detection zone.

DRM specification of the instrument

Parameter	Original	Units
Effective telescope area (A_{EFF})	3.821×10^4	cm^2
Optical bandpass (λ, $\Delta\lambda$)	550, 110	nm
Residual starlight (ζ)	5×10^{-11}	
Sharpness (ψ)	0.035	
Sampling criticality (κ)	1	
Pixel solid angle (Ω_x)	2.7×10^{-15}	steradians
Dark count rate (ξ)	0.001	$pixel^{-1}$
Read noise (γ)	2	per pixel
Inner working angle (IWA)	56.7	milliarcsec
Sensitivity ($\Delta mag_{0,MAX}$)	25	delta magnitudes

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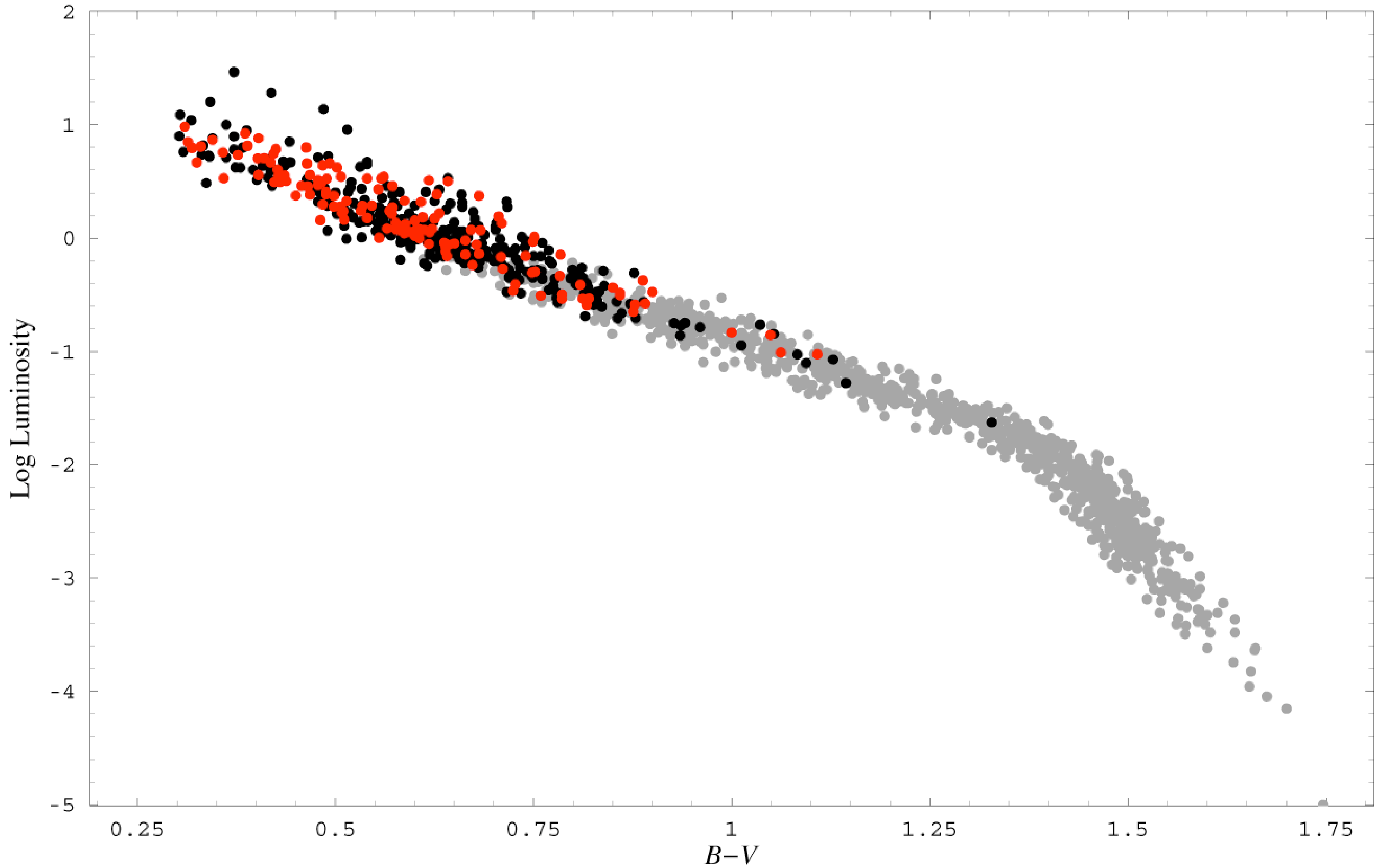
DRM specification of stars

Main Sequence
B–V > 0.2
No other star within 10 arcsec
d≤ 30 pc

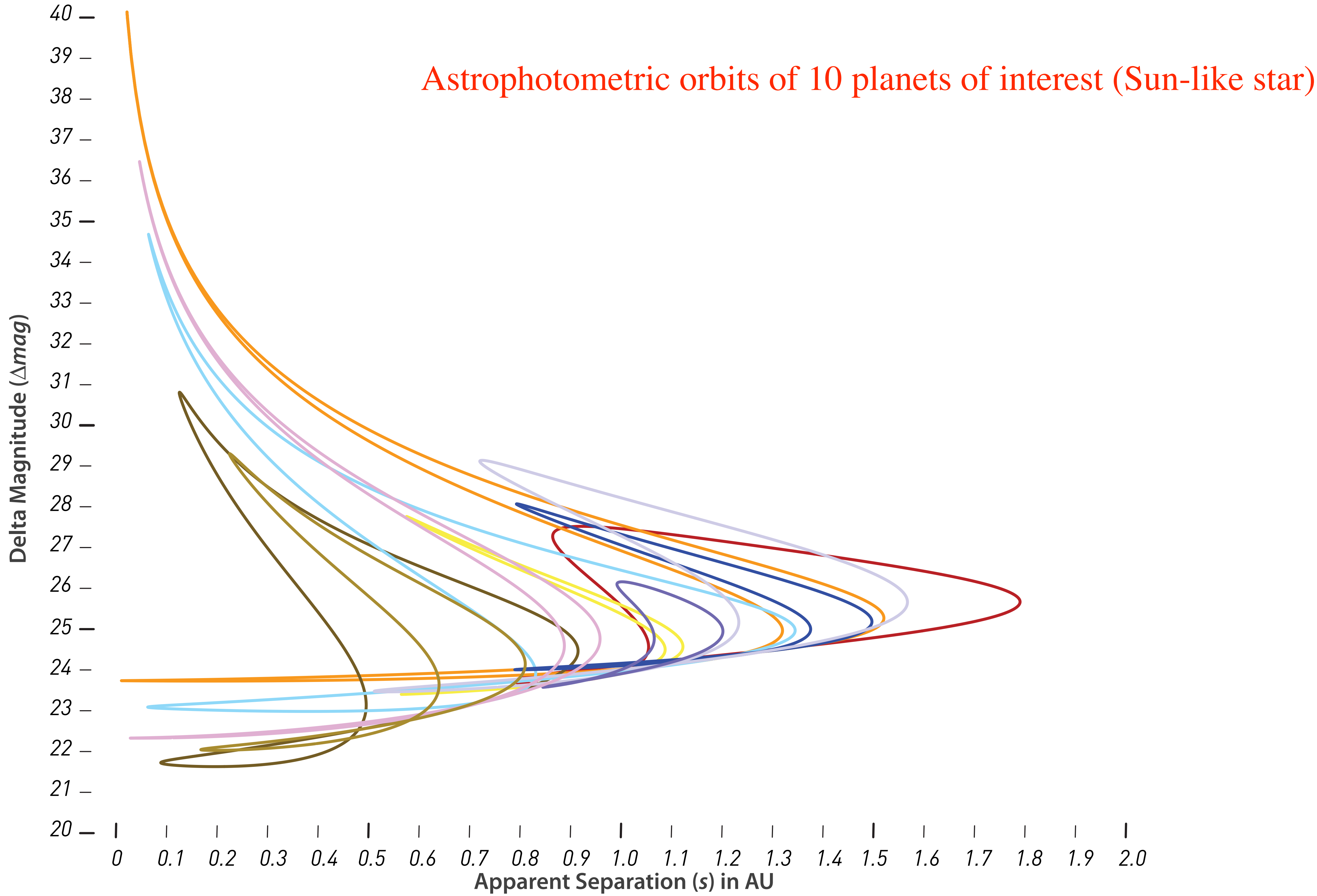


DRM specification of the planets of interest

Probability distributions

Parameter		Units	Rule
Semimajor axis (a)	$0.7\sqrt{L}$–$1.5\sqrt{L}$	au	uniform
Eccentricity (e)	0.0–0.35		uniform
Euler angle #1 (ψ)	0–2π		uniform
Euler angle #2 (θ)	0–π		uniform[1]
Euler angle #3 (ϕ)	0–2π		uniform
Initial phase (υ_0)	0–2π		uniform
Period (T_{ORB})	$365.25\, a^{1.5}\ \mathrm{m}_{\mathrm{STAR}}^{-0.5}$	days	computed
Effective planetary area ($p\ \pi R^2$)	0.33	$\pi R_{\oplus}{}^2$	fixed value
Phase function	$\frac{\sin\beta + (\pi - \beta)\cos\beta}{\pi}$		

Monte Carlo planets



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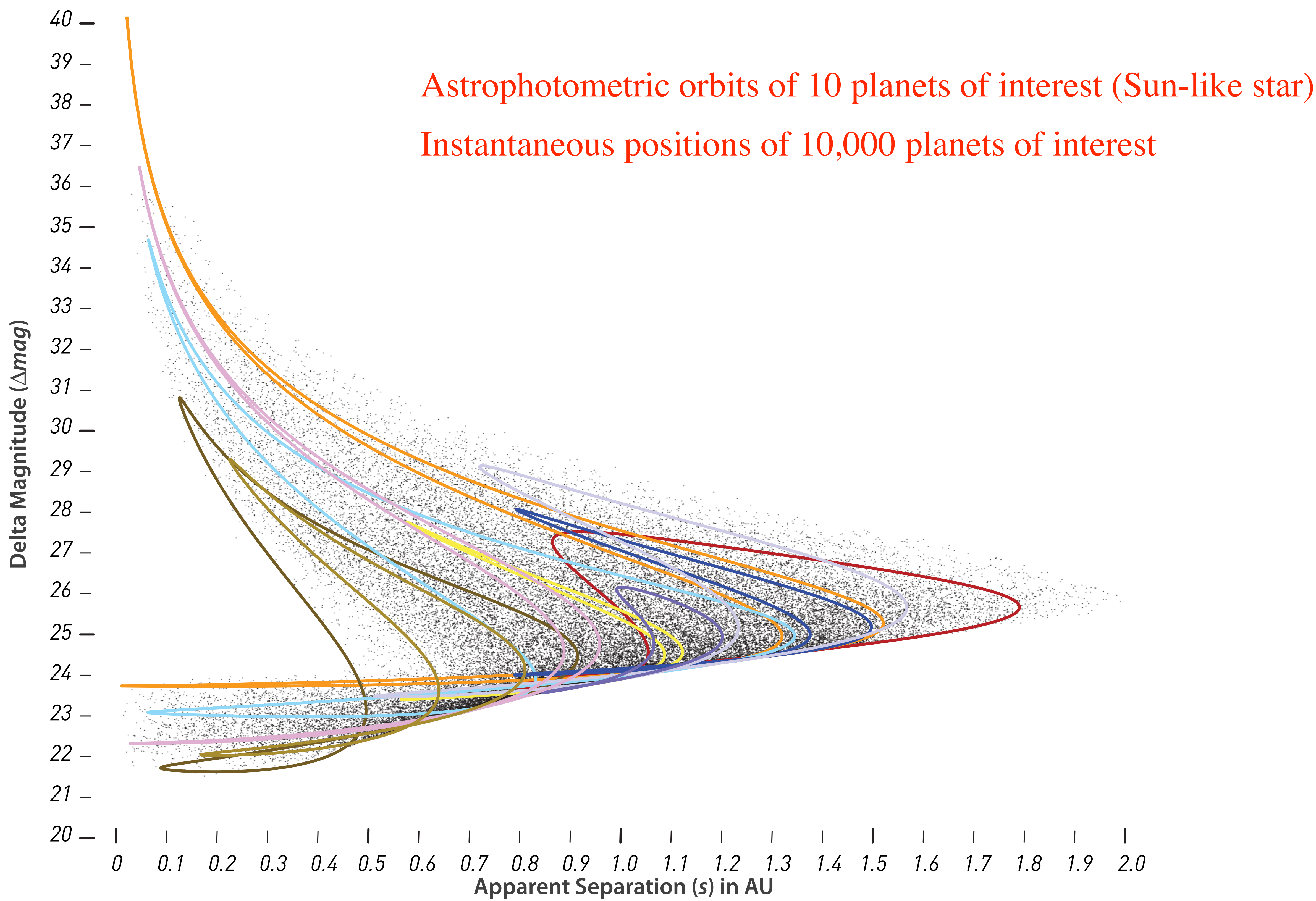
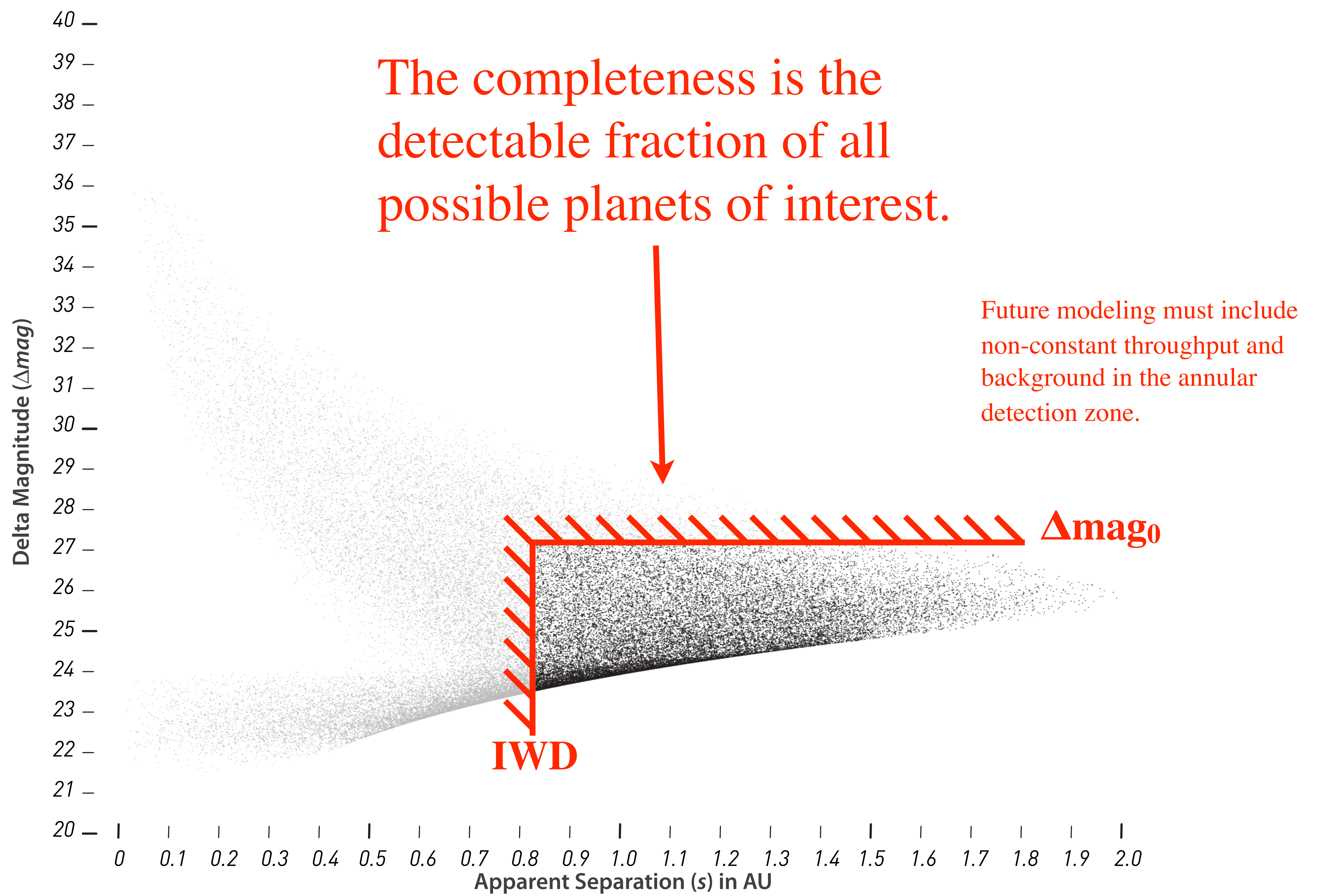


Completeness calculation



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Completeness/time is a natural metric for *TPF-C*

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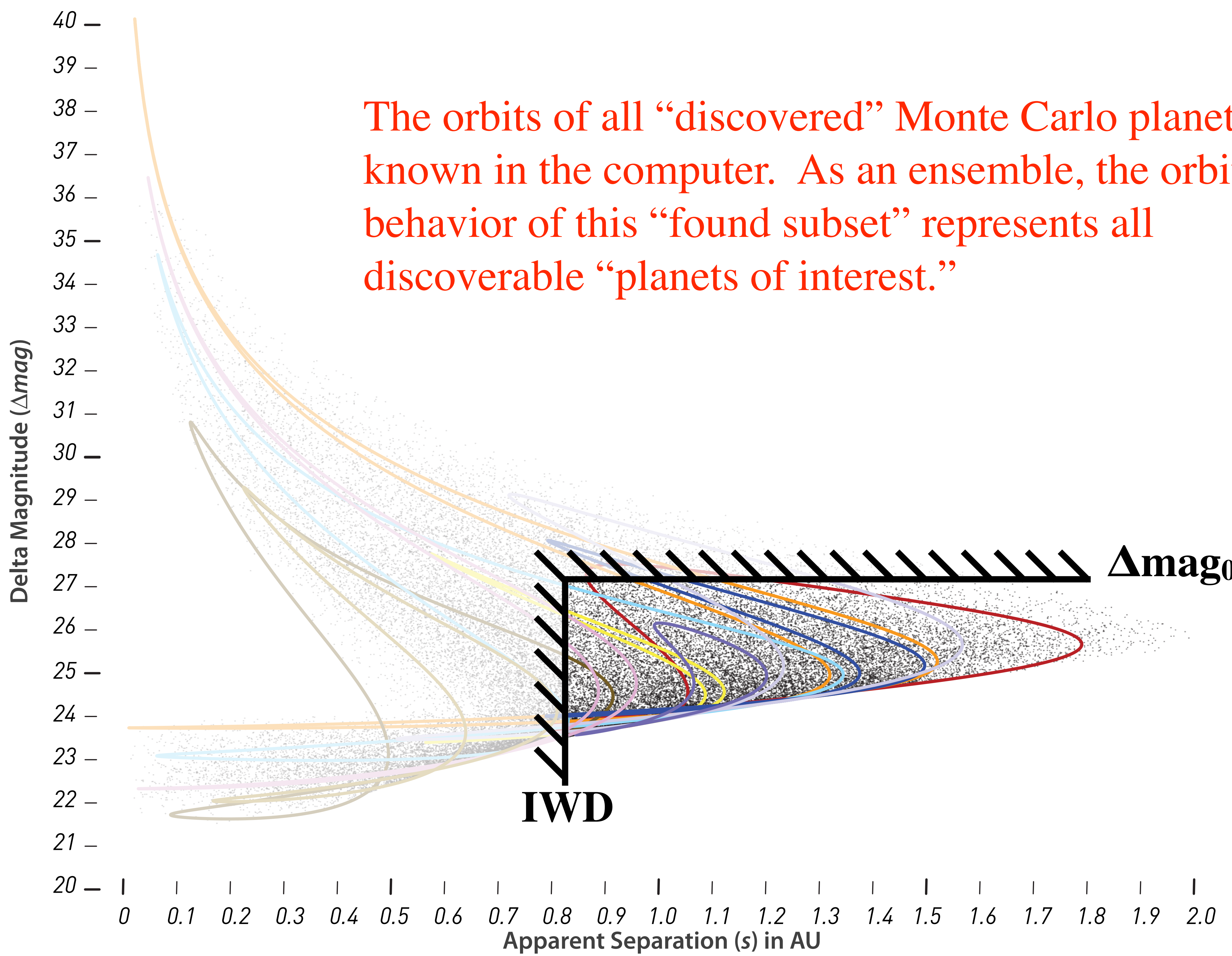
These aspects of design can *also* be studied and measured via the “found subset” of Monte Carlo planets.

“Found subset” of planets of interest

The orbits of all “discovered” Monte Carlo planets are known in the computer. As an ensemble, the orbital behavior of this “found subset” represents all discoverable “planets of interest.”



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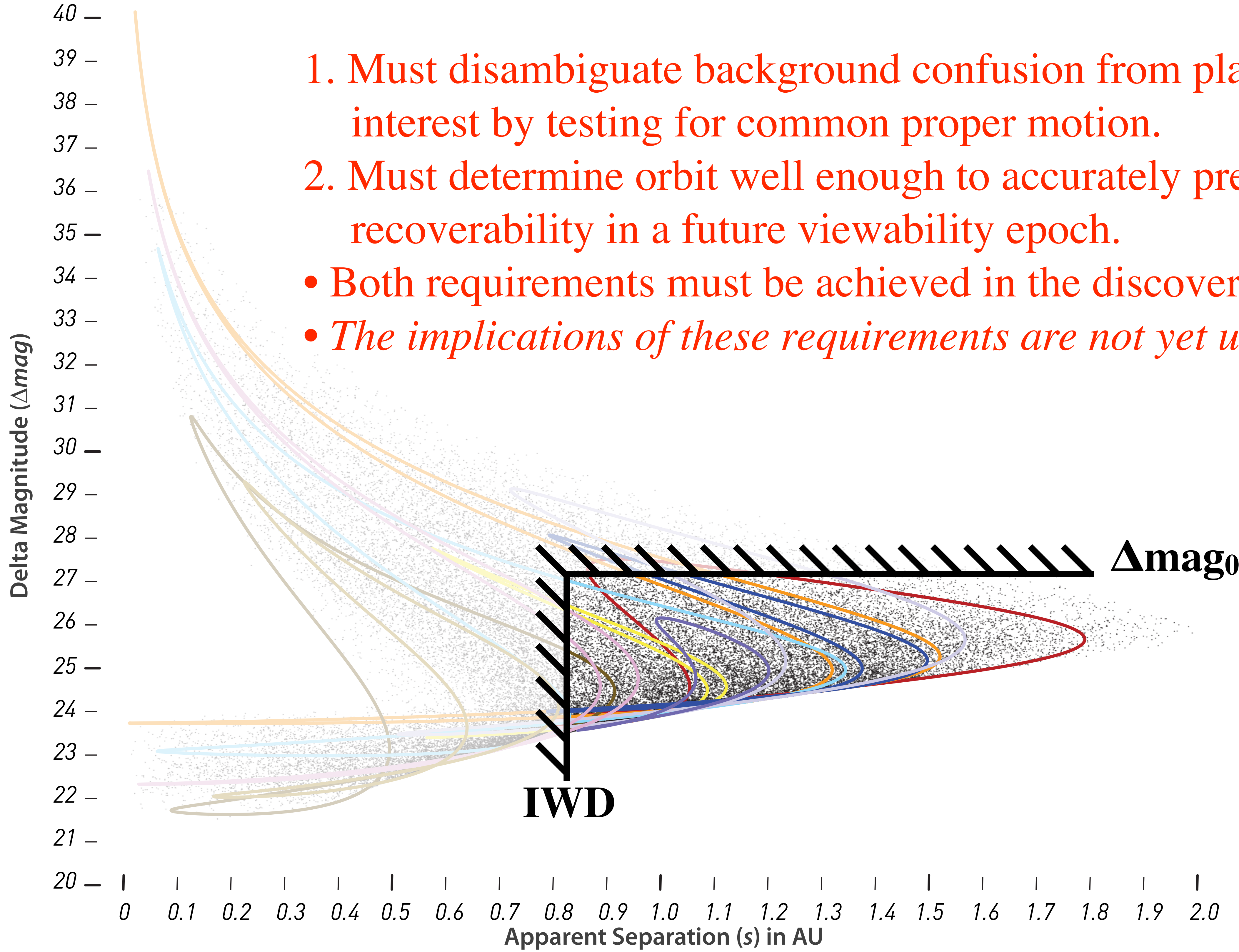
Discuss astrometry first Discuss operations second

TPF-C's astrometric requirements

1. Must disambiguate background confusion from planets of interest by testing for common proper motion.
2. Must determine orbit well enough to accurately predict recoverability in a future viewability epoch.

- Both requirements must be achieved in the discovery epoch.
- *The implications of these requirements are not yet understood.*



Preliminary metrics from science operations

1. Optimized total completeness achieved with one year of exposure time.
   - inherited from STDT, DRM
2. Astrometric accuracy at “detection” SNR.
   - motivated here
3. Average duration of planetary observability period
   - observability = viewability + detectability
   - motivated here
4. Sky size for choosing next target
   - intuitive
5. Slew time to limit of sky size
   - intuitive
6. Non-slewing overhead per observation
   - intuitive

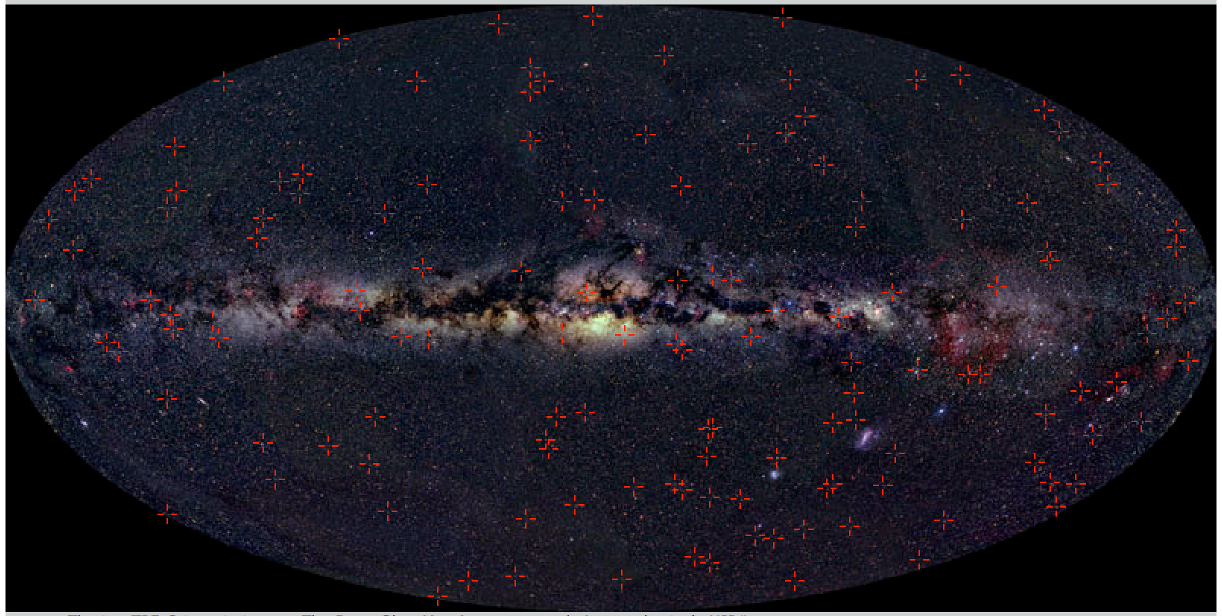
(Backup charts for Monte Carlo studies of confusion disambiguation, solar avoidance, and planetary recovery.)

StarVault: 136 most productive stars

http://sco.stsci.edu/starvault/

TPF-C's Top Target Stars

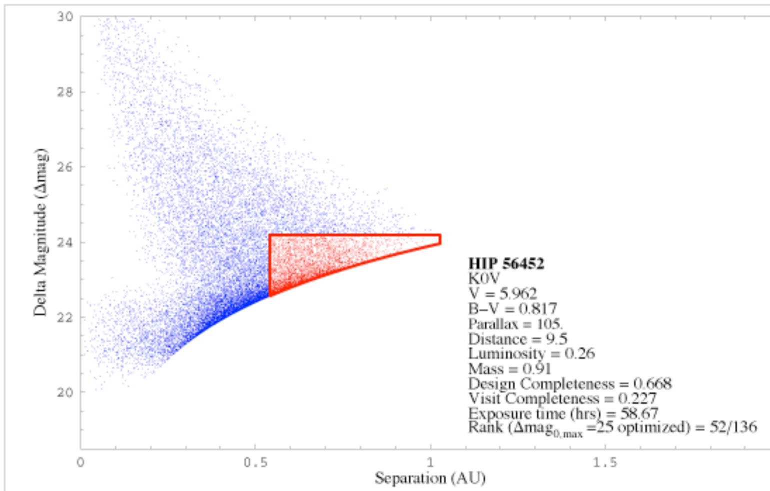
Details on the most productive stars for the coronagraphic Terrestrial Planet Finder mission (TPF-C)



The top TPF-C target stars on The Deep Sky. Mousing over crosshair reveals star's HIP#.

Display list in ascending order by: Rank

Rank	HIP#	Rank	HIP#	Rank	HIP#	Rank	HIP#
1	71683	35	47592	69	113357	103	71957
2	71681	36	53721	70	13402	104	51523
3	8102	37	25278	71	23311	105	26394
4	3821	38	5862	72	12653	106	33277
5	99240	39	112447	73	97675	107	19893
6	2021	40	56997	74	73996	108	27435
7	22449	41	28103	75	42438	109	86486
8	27072	42	99825	76	91438	110	34834
9	15510	43	86796	77	29800	111	98819
10	19849	44	50954	78	10138	112	950
11	1599	45	8362	79	92043	113	114924
12	108870	46	77952	80	75181	114	88972
13	64394	47	3909	81	40693	115	10798
14	105858	48	76829	82	107649	116	86614
15	14632	49	81300	83	43587	117	29860
16	57757	50	80337	84	32439	118	72567
17	78072	51	86736	85	34065	119	100017
18	96100	52	56452	86	35136	120	41926
19	12777	53	4151	87	7978	121	88694
20	64924	54	84862	88	38908	122	62207
21	15457	55	32480	89	18859	123	111449
22	7513	56	15330	90	3583	124	114948
23	23693	57	17651	91	97295	125	43726
24	57443	58	49081	92	98767	126	98470
25	16852	59	61174	93	50564	127	107350
26	116771	60	22263	94	25110	128	103389
27	24813	61	48113	95	36439	129	39780
28	73184	62	58576	96	110649	130	89348
29	114622	63	109422	97	544	131	40035
30	70497	64	3093	98	40702	132	34017
31	102485	65	910	99	59072	133	85235
32	29271	66	40843	100	29650	134	98959
33	59199	67	64792	101	16245	135	44897
34	71284	68	79672	102	26779	136	88175



STAR: $L \leftrightarrow B$-V | $d \leftrightarrow V$ | $L \leftrightarrow V$

COMPLETENESS: $C_1 \leftrightarrow V$ | $C_\infty \leftrightarrow V$ | C_1 / T_{exp} | $C_\infty \leftrightarrow C_1$

FOUND SUBSET: Δ_{mag} & s | a | ε | F_{ORB} | Depletion | a, ε & F_{ORB} | F_{PERM} & $T_{10\%LOST}$ | $P_{CONFPER}$ & F_{SOLAVD} | Proper Motion | Displacements | Periods | Recoverability

 # 52, HIP 56452 — Δ_{mag} & s

Distribution of Δ_{mag} & s for the found subset. Instrumental (s_0, Δmag_0) and stellar (L, P) factors combine to select different "found subsets" of planets for each star. Varying luminosity distorts and shifts the planetary distribution. The smallest detectable separation is determined by the central obscuration projected to the distance of the star. The red dots are the detectable planets out a sample of 20,000 habitable-zone planets with random orbital orientations and phases.

Stellar Identity and Interest

Hipparcos #: 56452
Other Names:
Known planet:
Miscellaneous:

Stellar Data

Spectral Classification : K0V
π, annual paralax: 104.84
d, distance: 9.53834 parsec
V: 5.96183 magnitude
B-V color: 0.817 magnitude
M_v: 6.06 magnitude
L, luminosity: 0.25731 solar units
m_{STAR}: 0.91 solar units
RA_{2000}: 173.625 degrees
Dec_{2000}: -32.833 degrees
μ_{RA}: -670.98 milliarsec/yr
μ_{Dec}: 823.84milliarsec/yr
Galactic Longitude: 284.778 degrees
Galactic Latitude: 27.3106 degrees
Ecliptic Longitude: 188.853 degrees
Eclipitc Latitude: -32.3143 degrees

VIEW SIMBAD RESULTS

***TPF-C* Basic Information**

Star #: 73
Productivity ranking : 52
IWD, inner working distance : 0.232139 au
Δmag_0, limiting delta magnitude: 24.1896 magnitude
T_{MAX}, maximum period: 254.126 day
F_{SOLAVD}, solar avoidance OK: 0.467 fraction of year star is observable

***TPF-C* Completeness Results**

T_{exp}: 58.6656 hour
C_1, first visit completeness : 0.22655
Productivity, C_1 / T_{exp}: 3.86172 milliplanets/hour
C_∞, ultimate completeness: 0.6683
Zenoic steps (1σ, 2σ, 3σ): 3, 8, 15

***TPF-C* Found-subset Results**

$T_{10\%LOST}$, depletion time: 4.21587 day
Mean displacement in $T_{10\%LOST}$: 0.0561389 au
F_{DISC}: 0.519 fraction of year background confusion discriminable
F_{DISC} & F_{SOLA}: 0.467 fraction of year observable and discriminable
F_{ORB}: 0.385 mean fraction of orbit detectable
$F_{S\text{-}MID}$, fractional mid separation: 0.763253 (s_{MIN} + s_{MAX}) / (2a_{MAX} (1 + e_{MAX}))
F_{PERM}: 0.0543817 permanently detectable fraction of all orbits
F_{PERM} / C_∞: 0.0813731 permanently detectable fraction of detectable orbits

Online completeness calculator

http://maranello.stsci.edu:9006/webMathematica/combined.html

Input

Step1: Input for sample generation

Number of Monte Carlo planets 10000

Planetary radius in Earth radii 1

Geometric albedo .33

Minimum semimajor axis (AU) .7

Maximum semimajor axis (AU) 1.5

Power law of semimajor axis probability distribution 0

Minimum eccentricity 0

Maximum eccentricity .35

Power law of eccentricity probability distribution 0

Step 2: Specify the Star

Stellar luminosity in solar luminosities 0.26499

Stellar parallax in milliarcsec 96.33

Step 3: Specify the Instrument

Inner working angle in arcsec 0.05672

Limiting delta magnitude 25

Compute the Completeness

Output

The calculated completeness is:

0.2051

Parameters used for calculations

Sample
Number of Monte Carlo planets: 10000
Planetary radius in Earth radii: 1
Geometric albedo: .33
Minimum semimajor axis (AU): .7
Maximum semimajor axis (AU): 1.5
Power law of semimajor axis probability distribution: 0
Minimum eccentricity: 0
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Star
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Instrument
Inner working angle in arcsec: 0.05672
Limiting delta magnitude: 25

References

A Design Reference Mission (DRM) for *TPF-C*

Brown, R. A., Hunyadi, S. L., & Shaklan, S. B., 2006

http://sco.stsci.edu/tpf_downloads/TPF-C_DRM.pdf

StarVault: Details on the Most Productive Stars for *TPF-C*

http://sco.stsci.edu/starvault/

Completeness Calculator

http://maranello.stsci.edu:9006/webMathematica/combined.html

“Obscurational Completeness,” Brown, R. A. 2004, ApJ. 607: 1003–1013.

“Single-Visit Photometric and Obscurational Completeness,” Brown, R. A. 2005, ApJ 624: 1010–1024.

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“Single Visit Completeness Optimization,” Hunyadi, S., Shaklan, S, & Brown, R. A., 2006, (Submitted to ApJ.)

“The Roles of Technical Performance in Selecting Target Stars for TPF-C,” Brown, R. A., 2006, http://sco.stsci.edu/tpf_downloads/on_target_stars.pdf

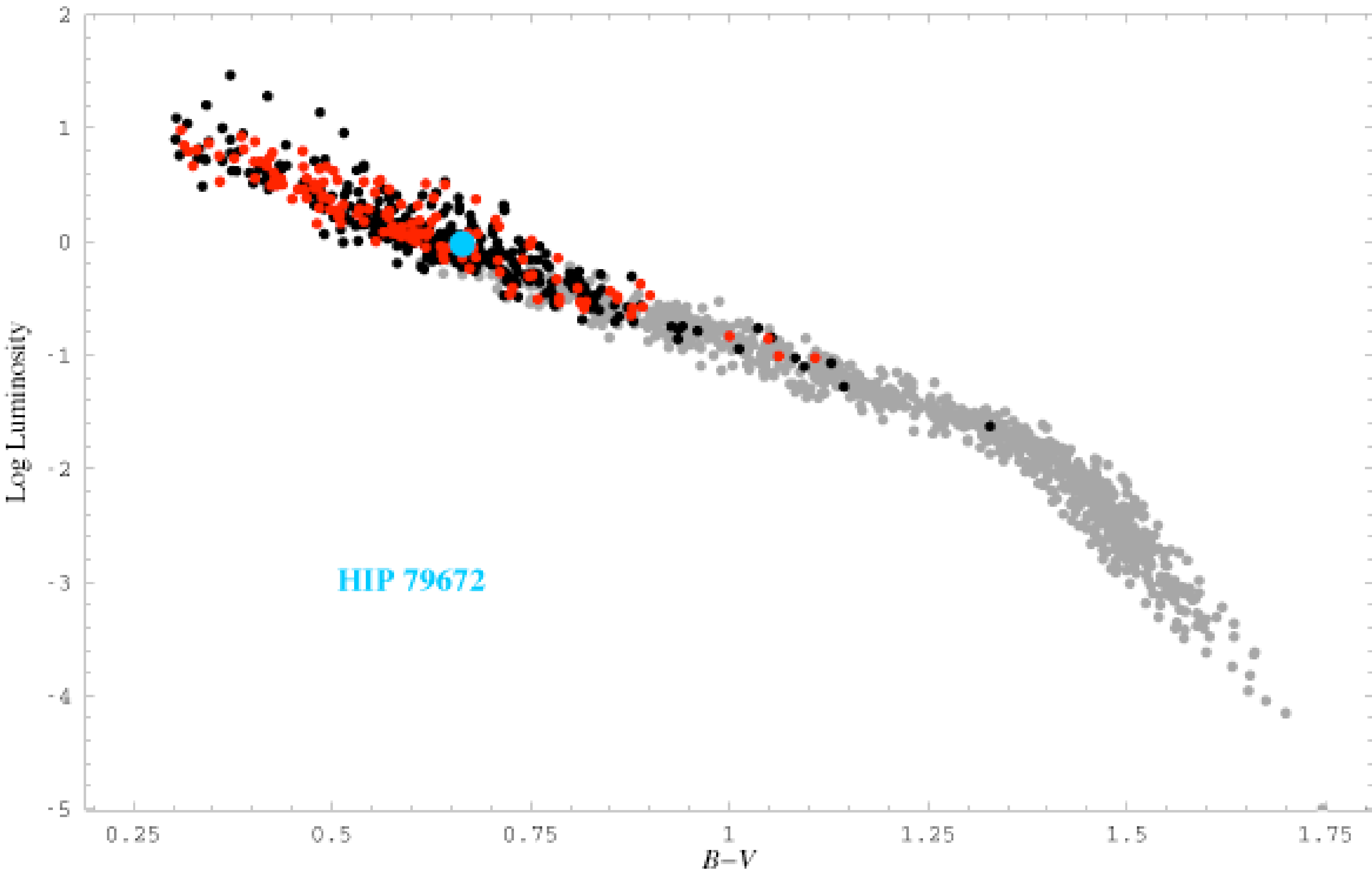
“Chasing Earth-like Planets,” Brown, R. A., 2006, http://sco.stsci.edu/tpf_downloads/chasing_earths.pdf

Backup Charts

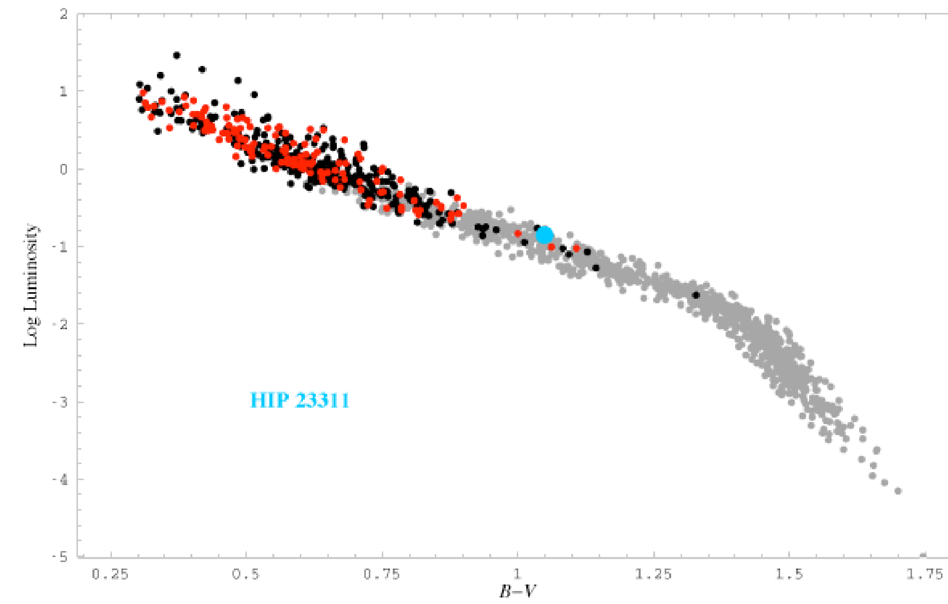
Monte Carlo studies of confusion disambiguation, solar avoidance, and planetary recovery.

Particular stars for illustration

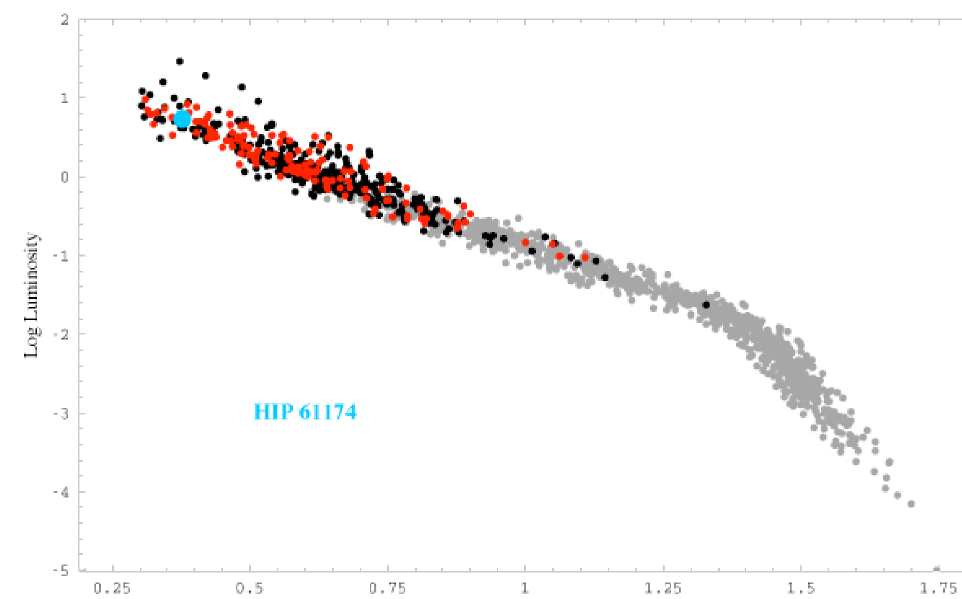
#68 **HIP 79672** ***L*** **= 0.95**



#71 **HIP 23311** ***L*** **= 0.14**

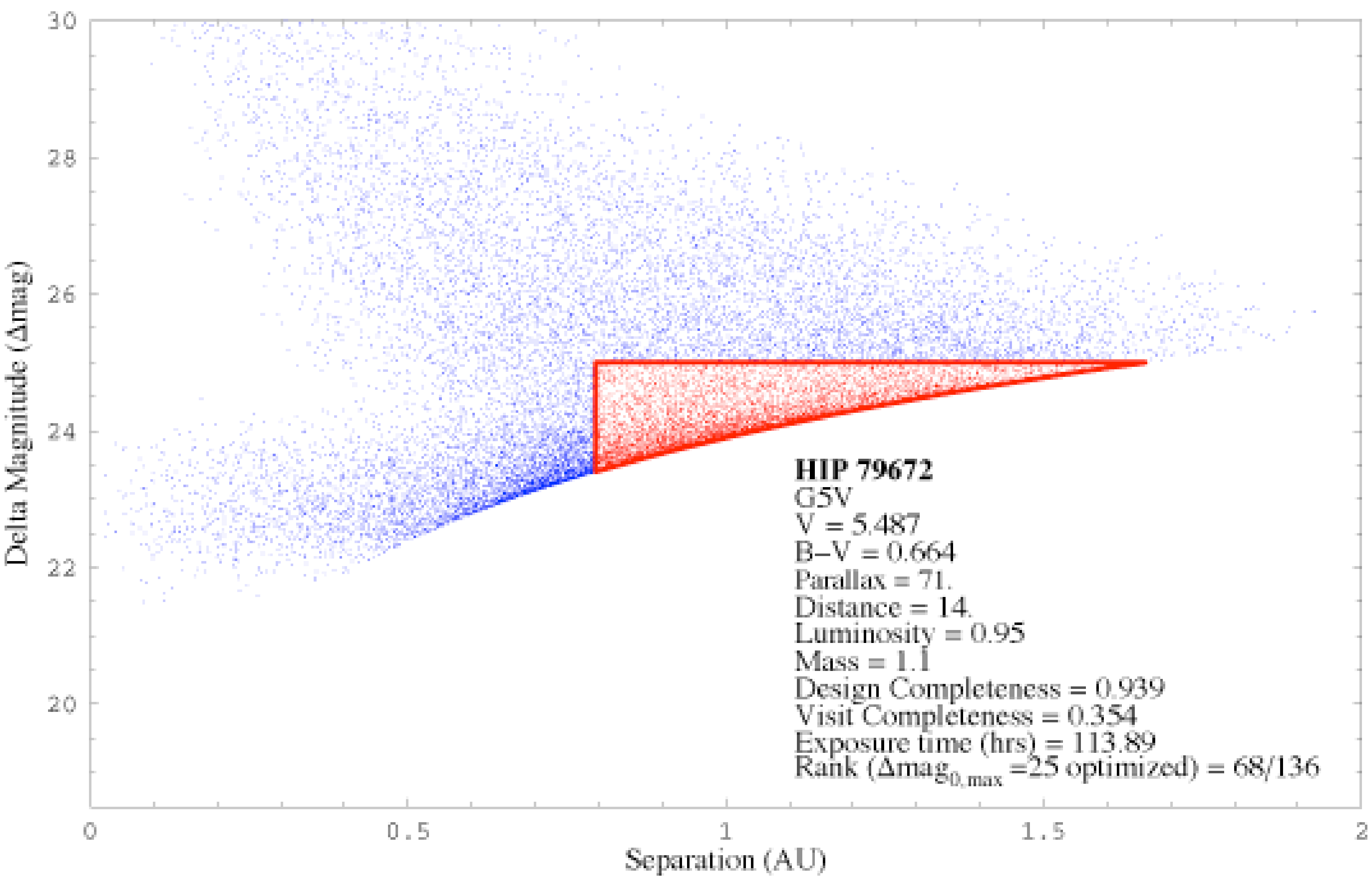


#69 **HIP 61174** ***L*** **= 5.4**

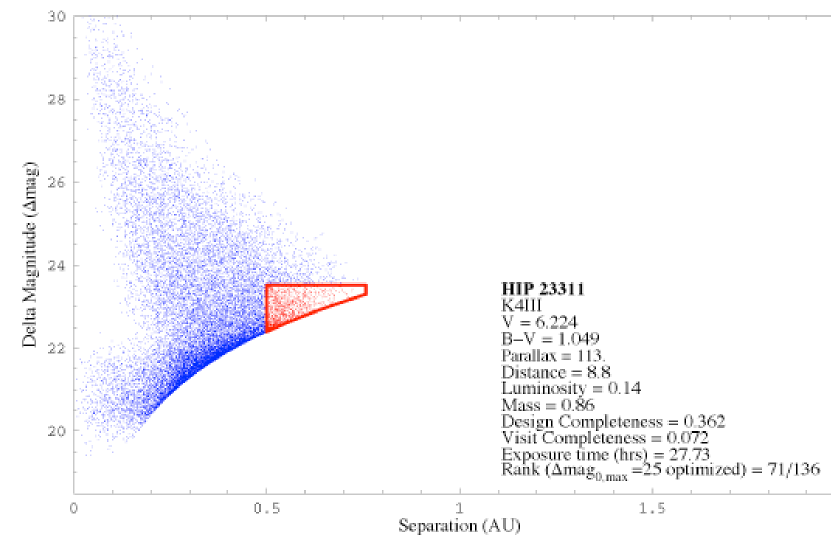


Variation of found subset with stellar distance & luminosity

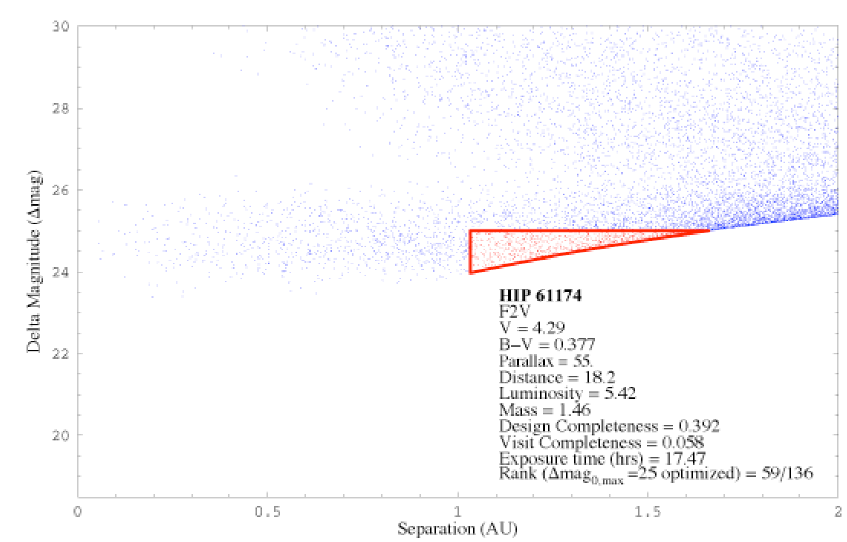
#68 **HIP 79672** ***L* = 0.95**



#71 **HIP 23311** ***L* = 0.14**

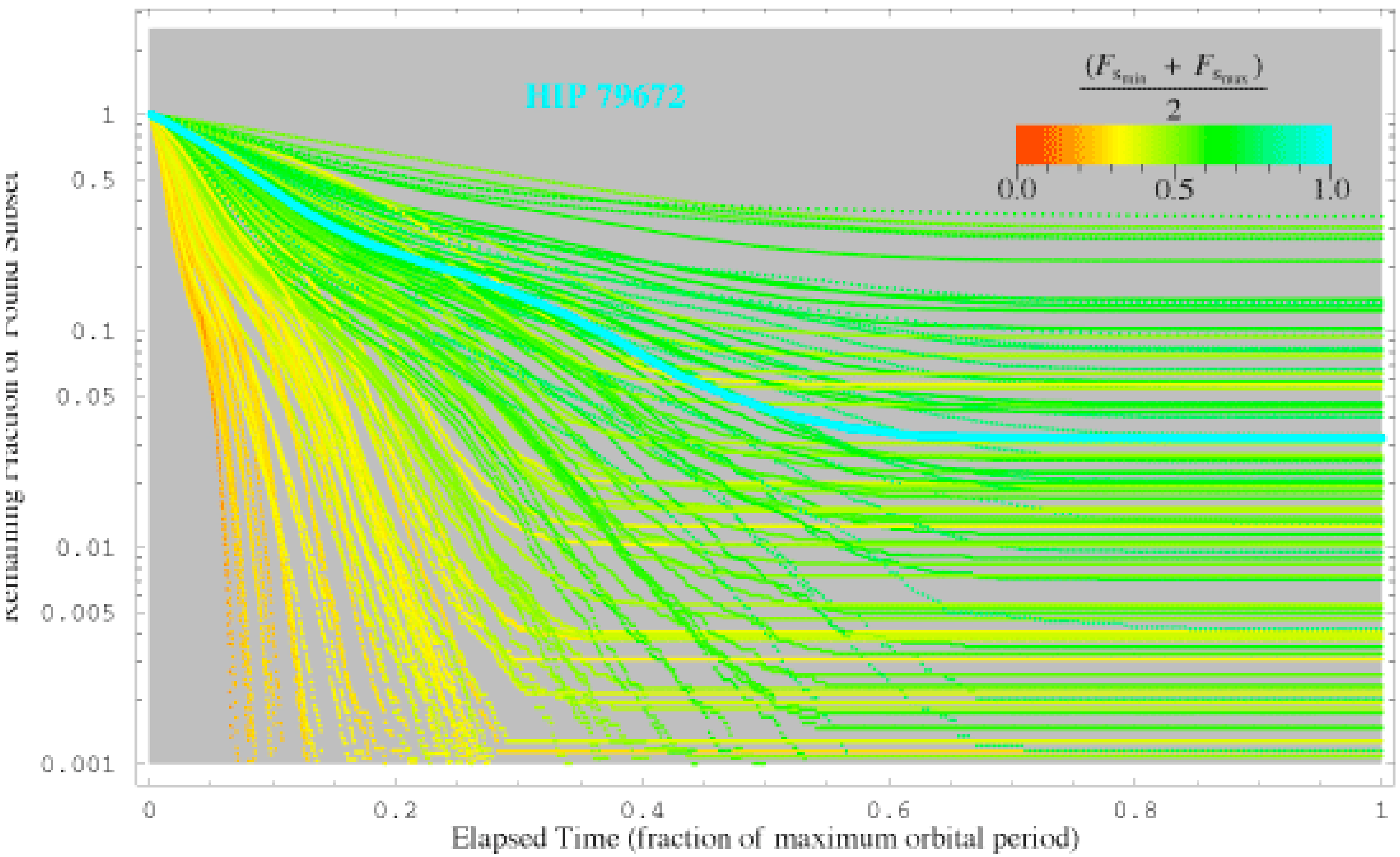


#69 **HIP 61174** ***L* = 5.4**

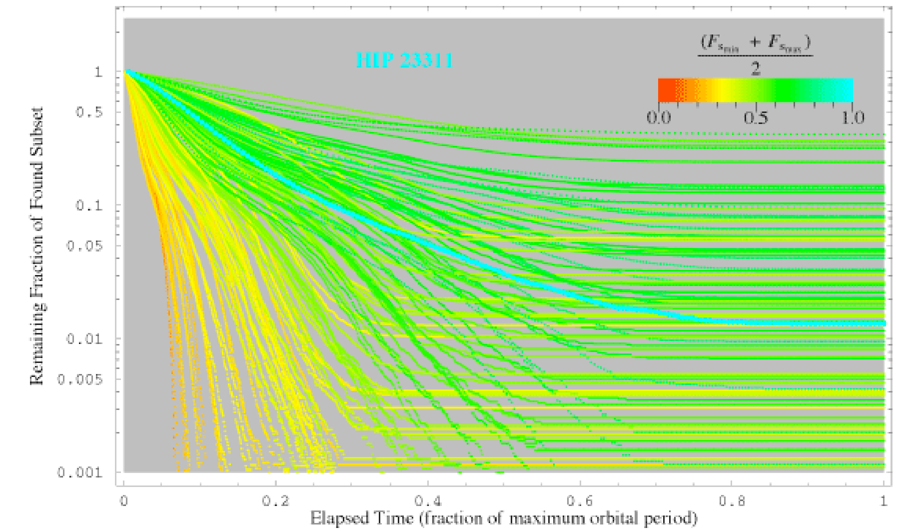


Confusion: depletion of the found subset

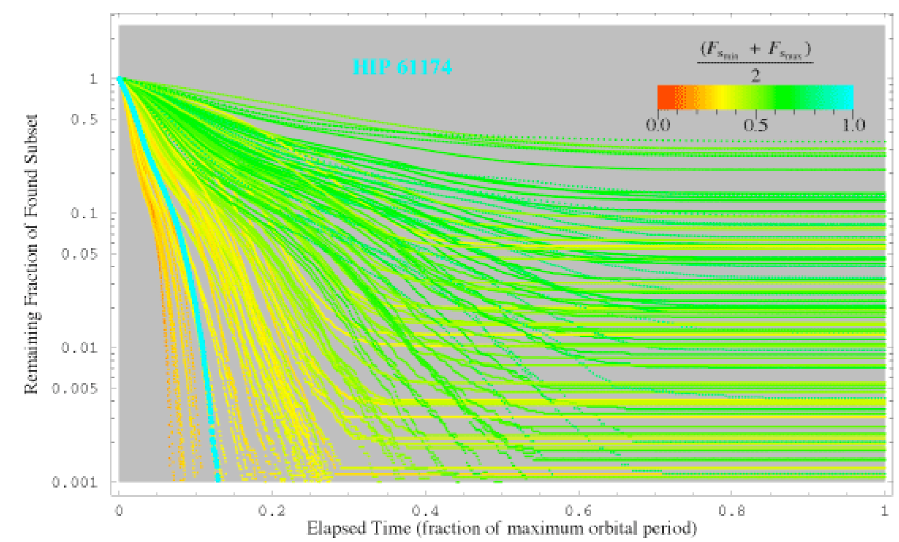
#68 HIP 79672 $L = 0.95$



#71 HIP 23311 $L = 0.14$



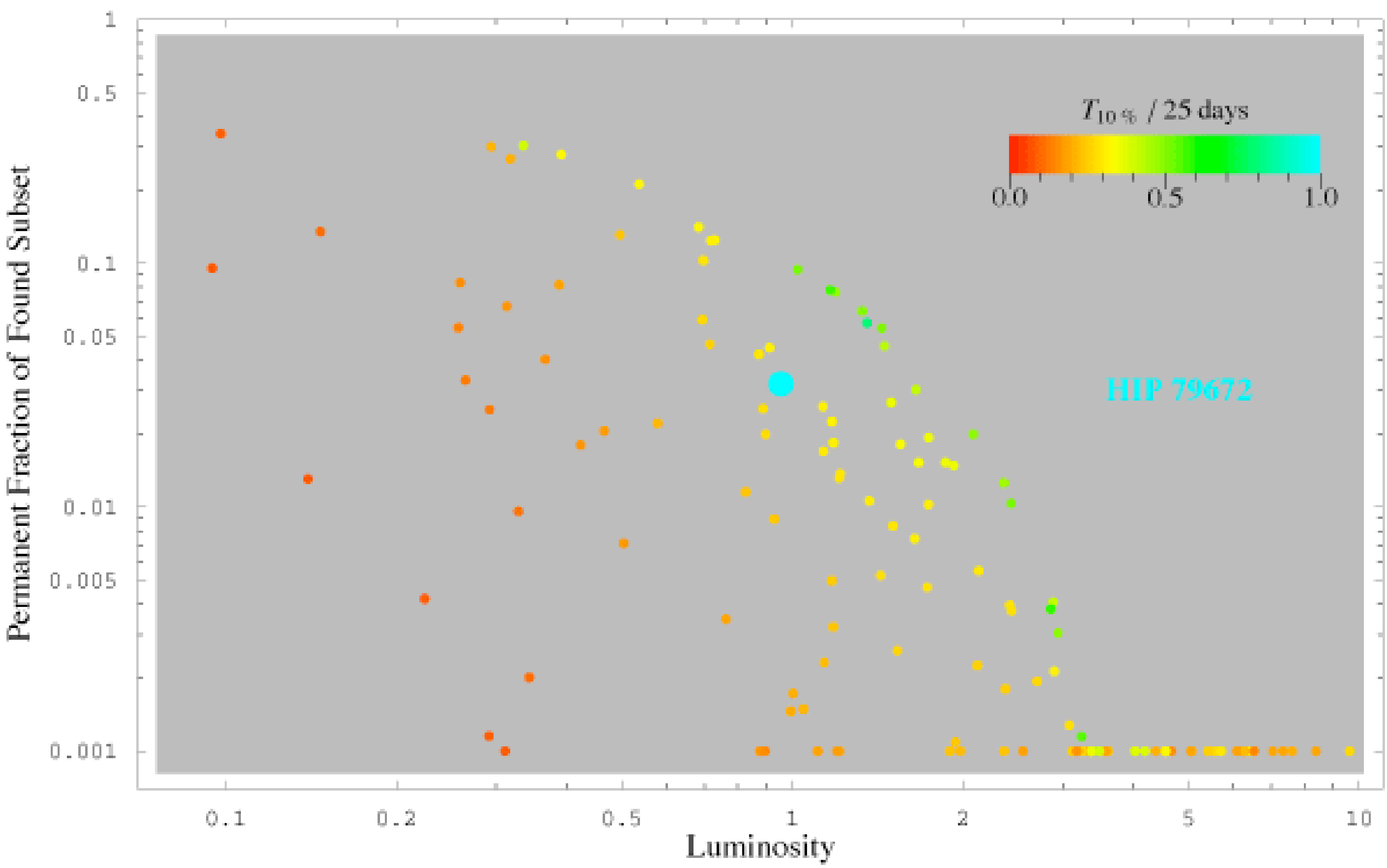
#69 HIP 61174 $L = 5.4$



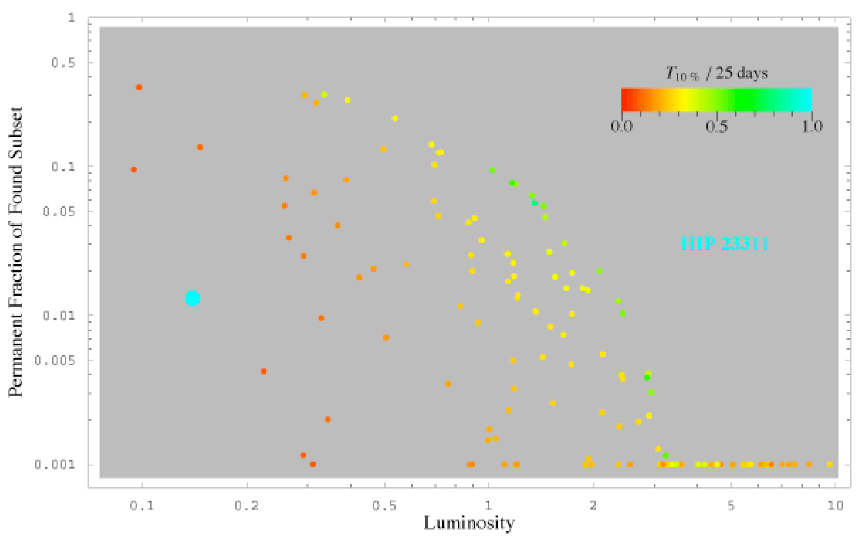
For 136 stars, the mean value of $T_{10\%LOST}$ is 8.4 days. Values range from 2.5 to 25 days.

Confusion: $T_{10\%\text{LOST}}$ & permanent fraction

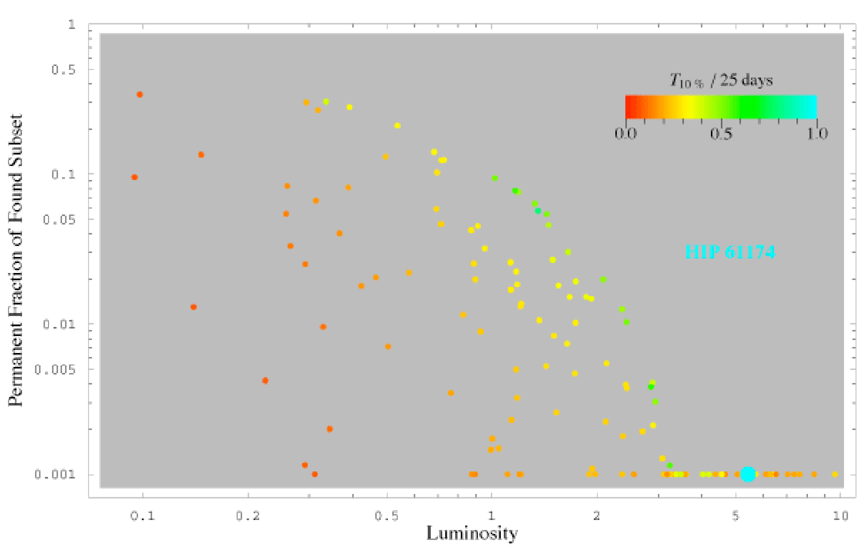
#68 HIP 79672 *L* = 0.95



#71 HIP 23311 *L* = 0.14

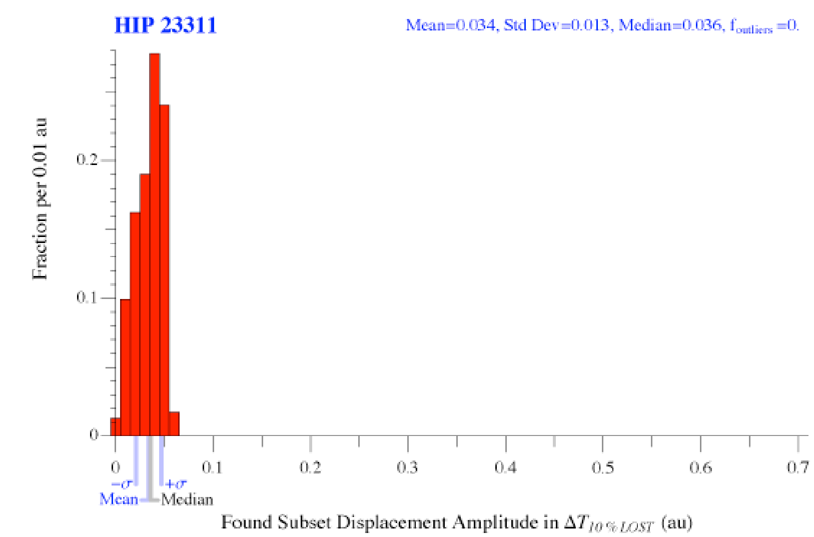


#69 HIP 61174 *L* = 5.4

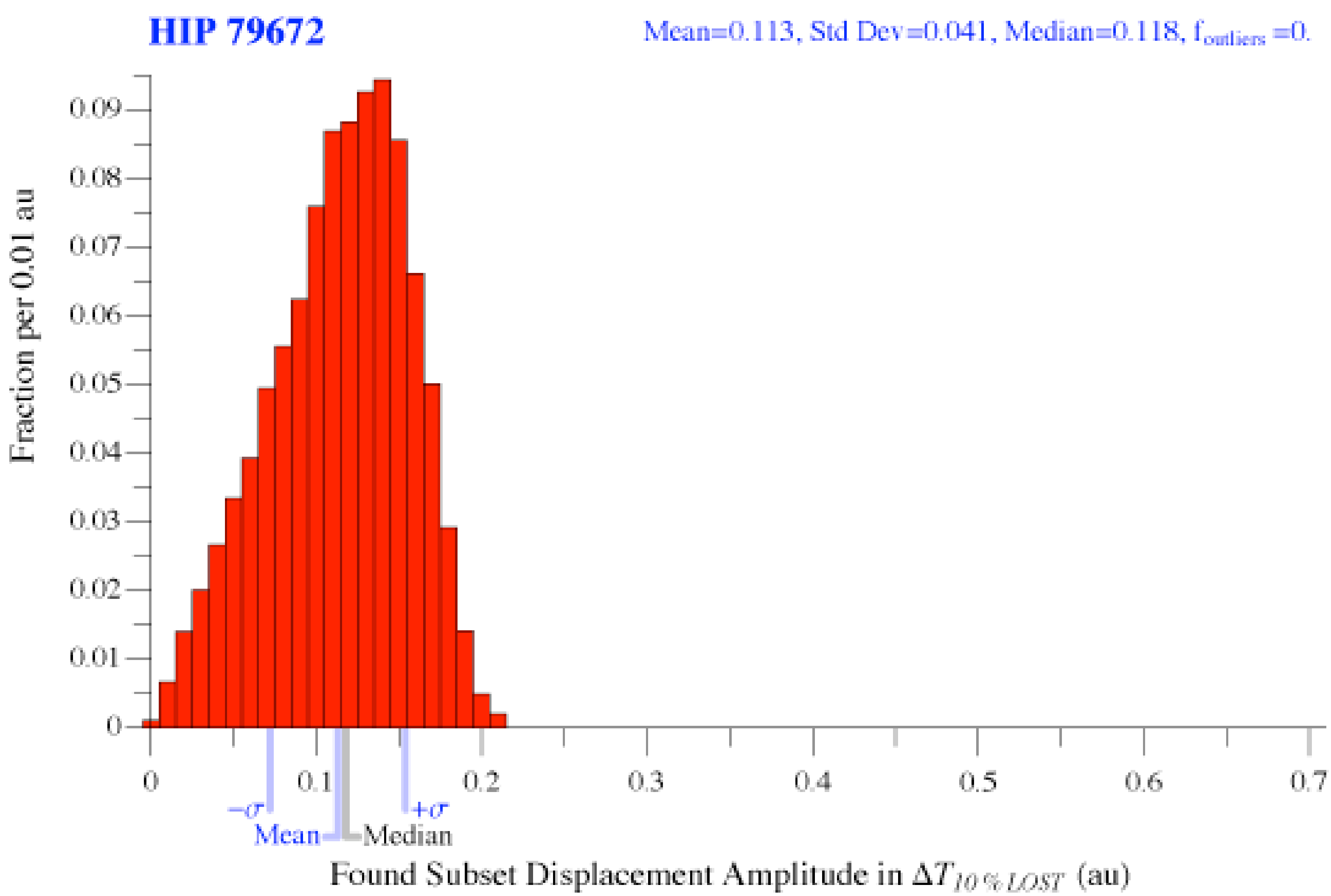


Confusion: planetary displacements in $T_{10\%\mathrm{LOST}}$

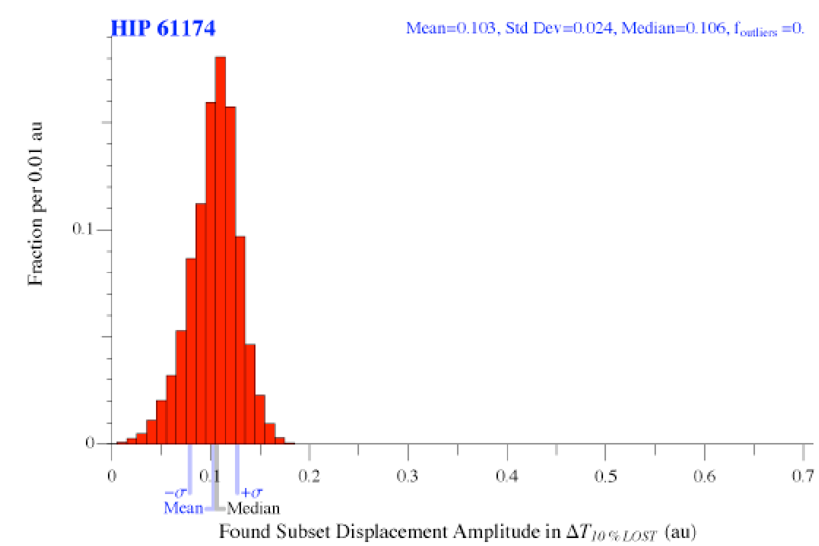
#71 HIP 23311 $L = 0.14$



#68 HIP 79672 $L = 0.95$



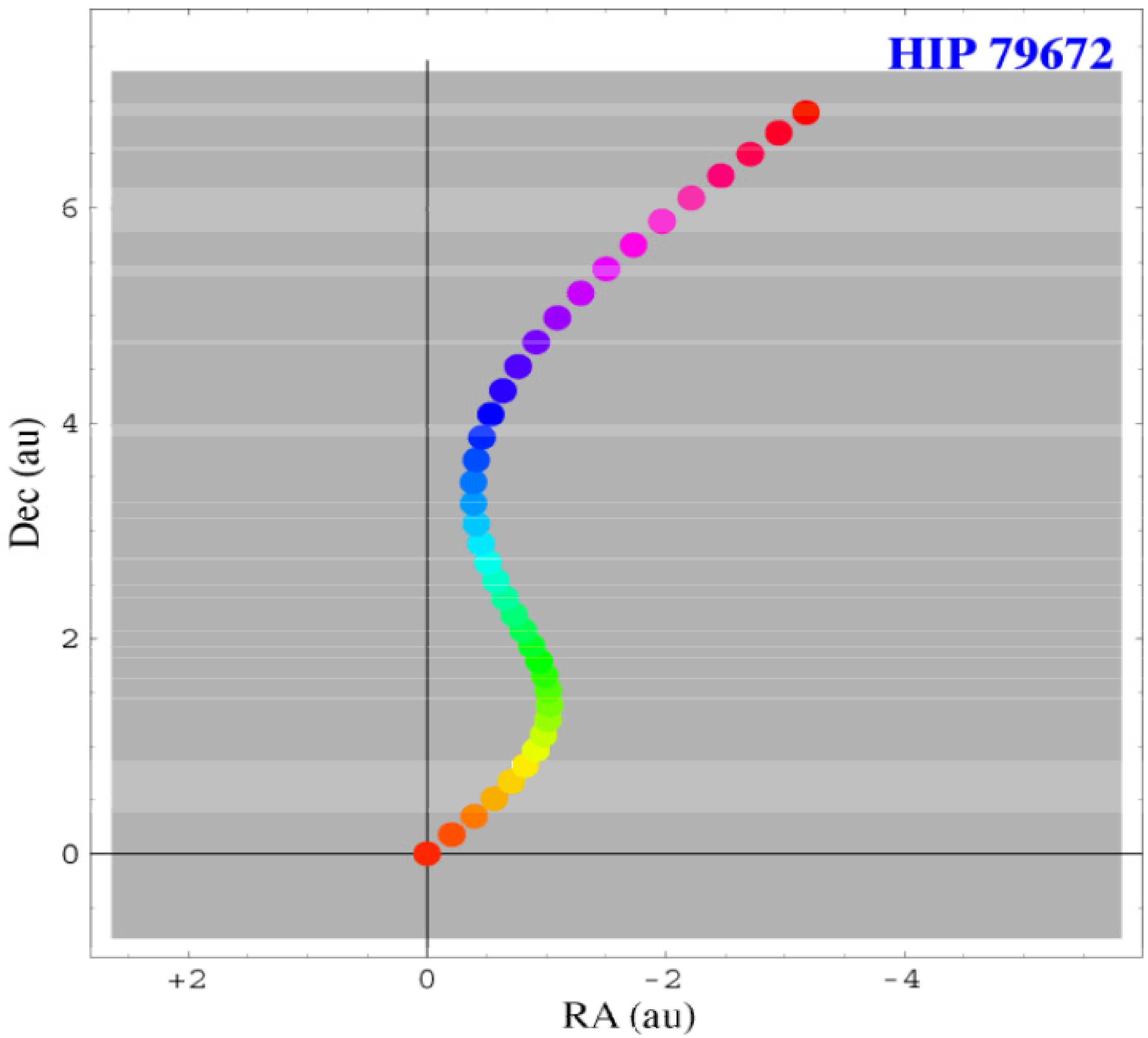
#69 HIP 61174 $L = 5.4$



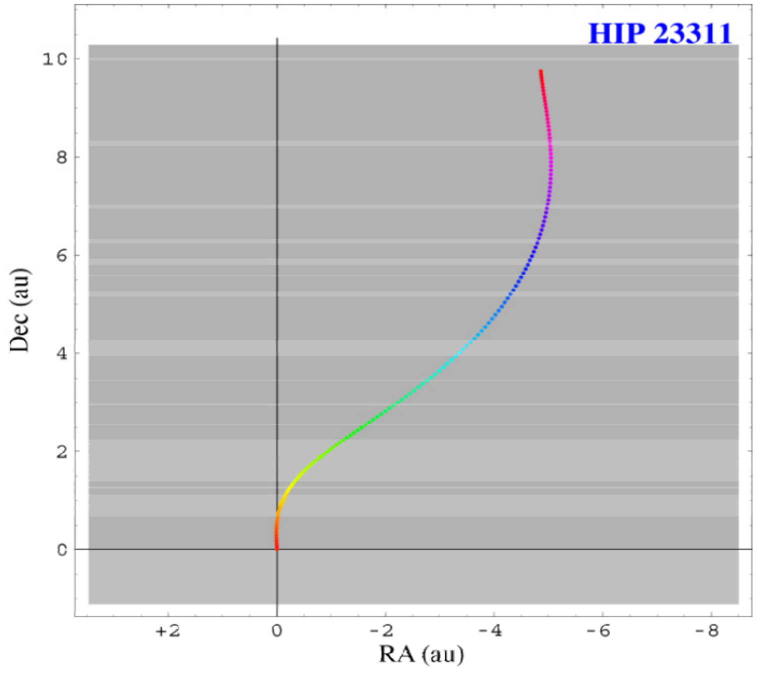
For 136 stars, the mean amplitude of the mean planetary displacement in $T_{10\%\mathrm{LOST}}$ is 0.11 au. Values range from 0.03 to 0.32 au.

Confusion: proper motion

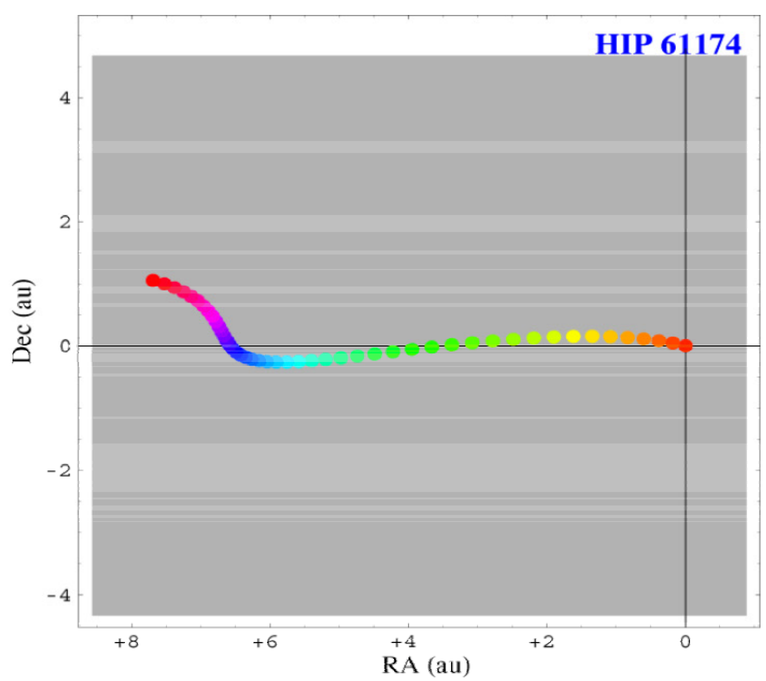
#68 HIP 79672 $L = 0.95$



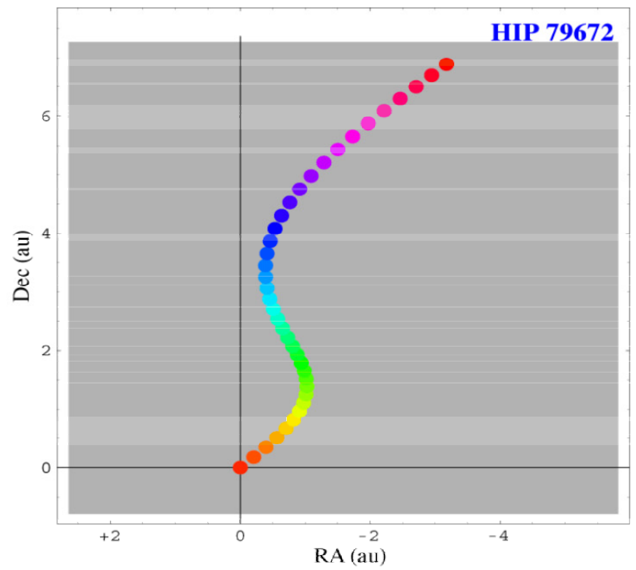
#71 HIP 23311 $L = 0.14$



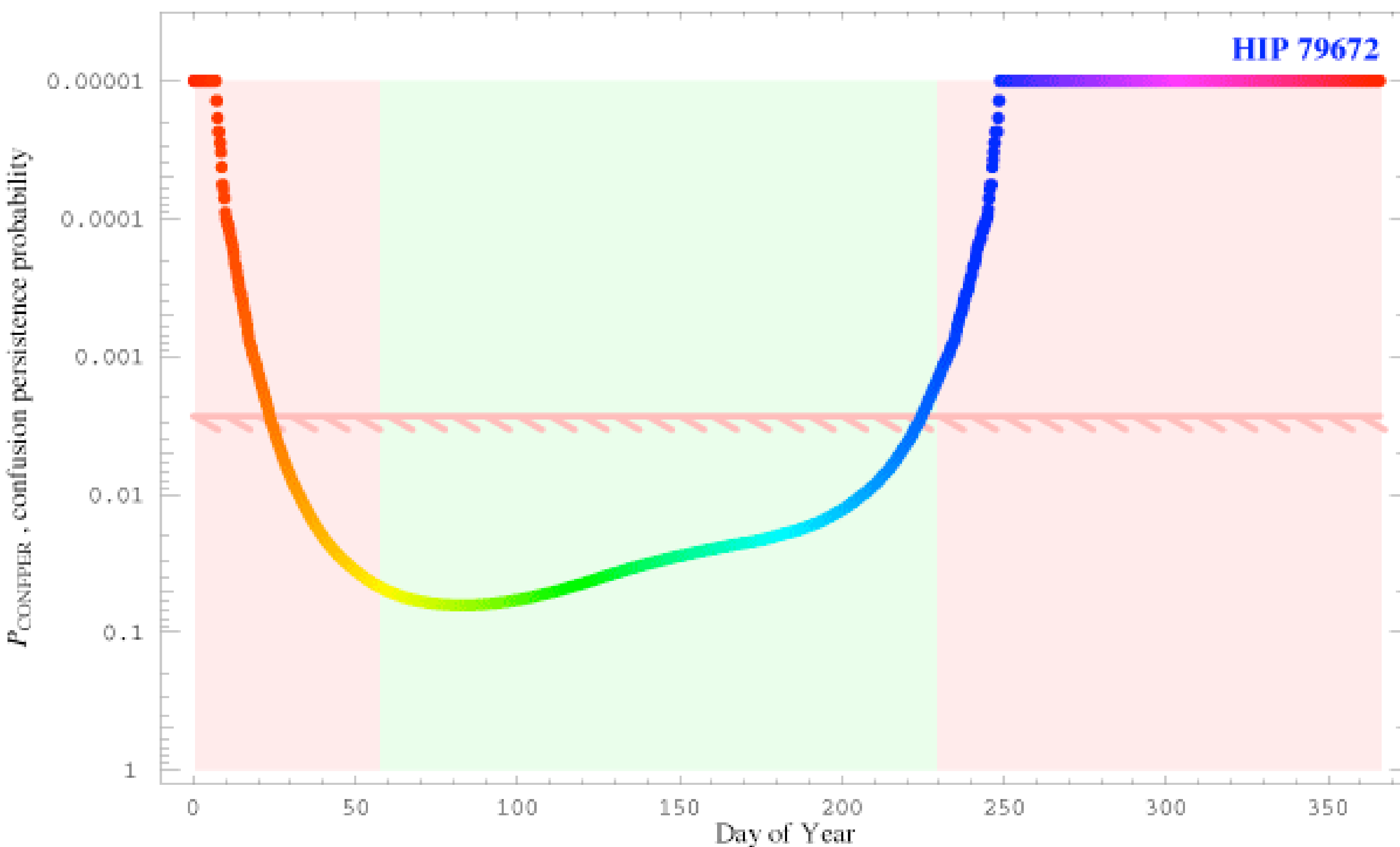
#69 HIP 61174 $L = 5.4$

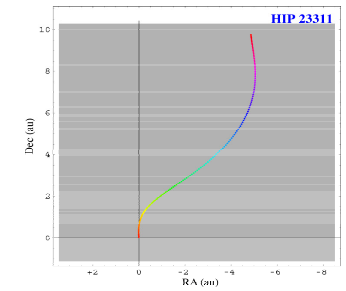


Solar avoidance & confusion disambiguation

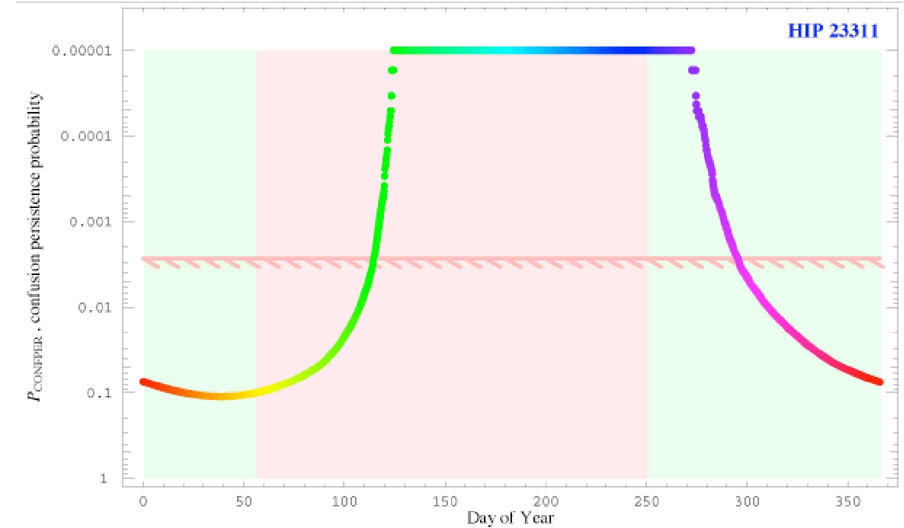


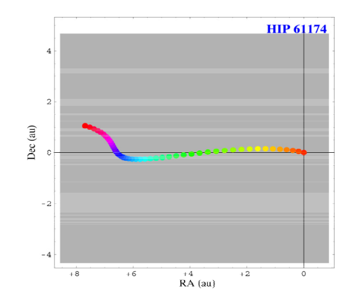
#68 HIP 79672 *L* = 0.95



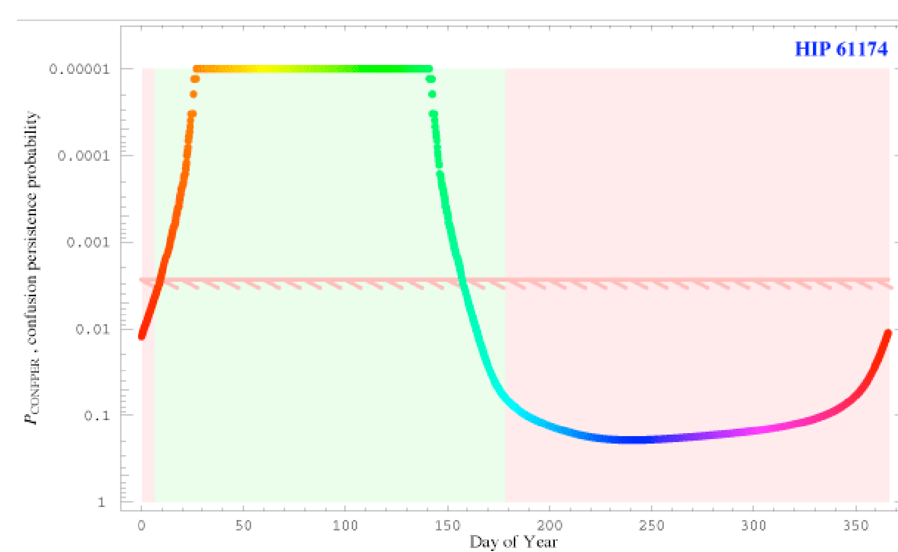


#71 HIP 23311 *L* = 0.14



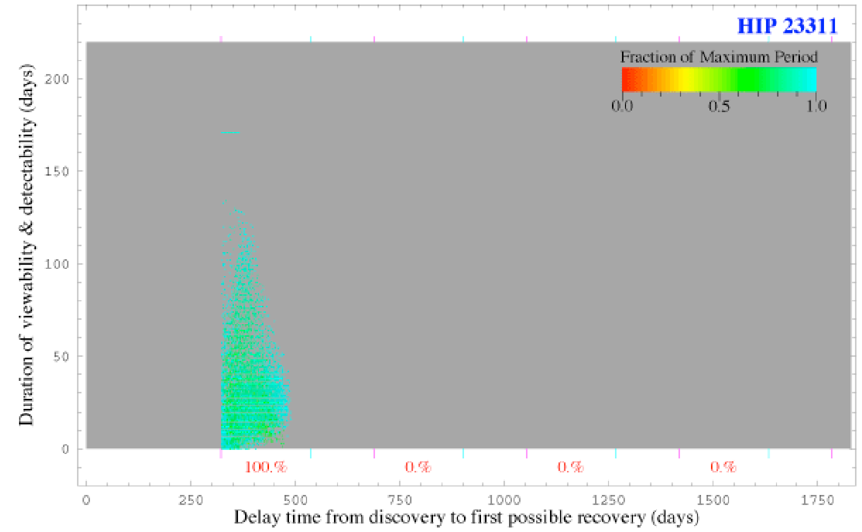


#69 HIP 61174 *L* = 5.4

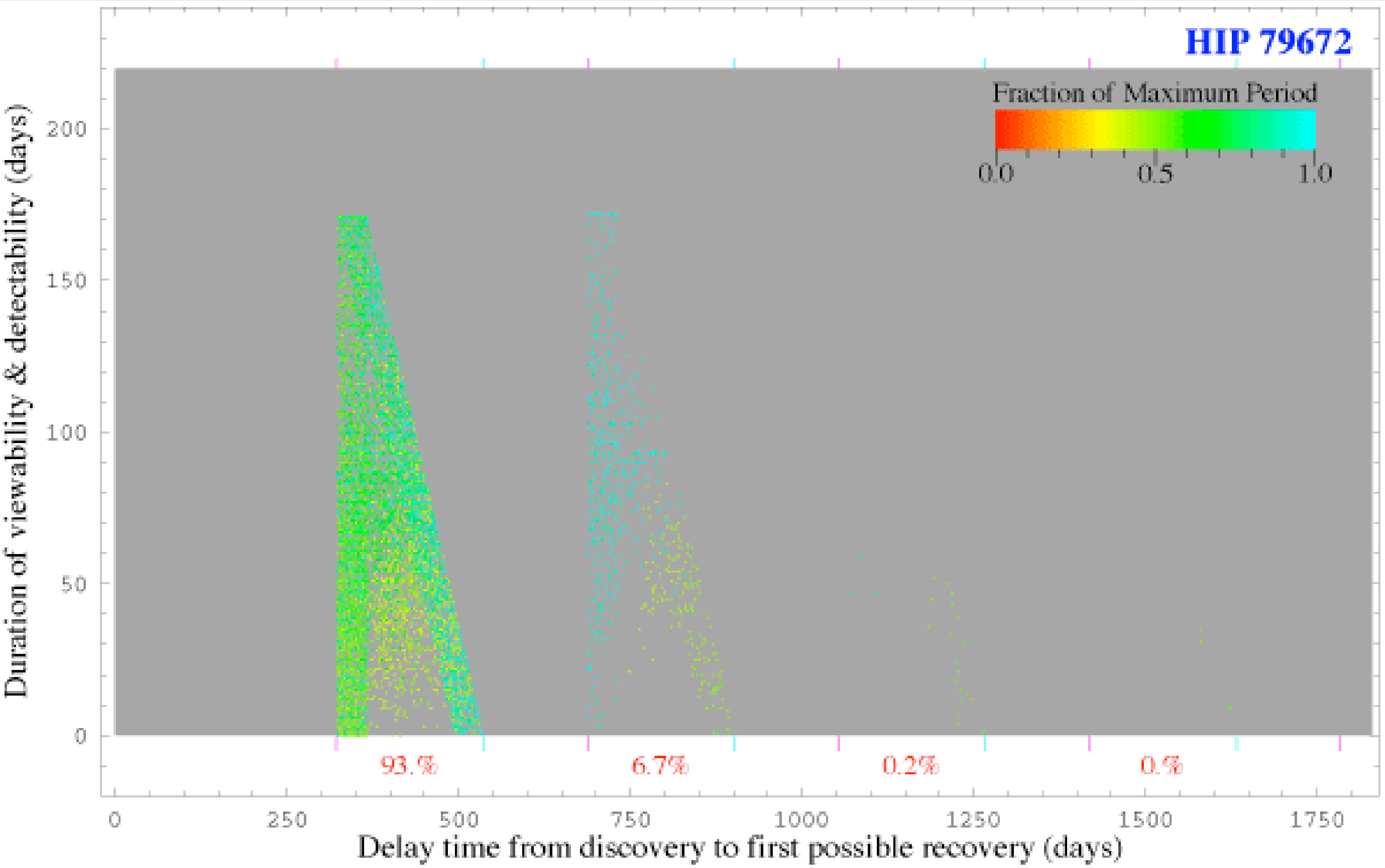


Planetary recovery

#71 HIP 23311 $L = 0.14$



#68 HIP 79672 $L = 0.95$



#69 HIP 61174 $L = 5.4$